Adaptive Digital Distance Relay for SSSC Based Double-Circuit Transmission Line Using Phasor Measurement Unit

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Summary-The existence of mid-point series FACTS devices leads to degrade the performance of mho relay, leading in erroneous estimation of fault location i.e. over or under-reach for wide variation in network parameters. This research article proposes a novel mho relay algorithm to improve the performance of distance relay in presence of FACTS device using phasor measurement unit (PMU). First, the complete model of transmission system employing SSSC (static synchronous series compensator) and its control strategy is described analytically, where the error introduced in measurement of impedance due to SSSC on the performance of distance relay. Secondly, a novel mho relay procedure is developed based on PMU to protect the first zone of double-circuit transmission line for SLG (single line-to ground) fault. The proposed work is analysed and simulated with 48-pulseSSSC carried out with Bergeron model of transmission line using PSCAD® computer simulation. Finally, the simulation results represent that the suggested adaptive scheme is truthful, reliable and secure with change in compensation level of SSSC.

Keywords: Adaptive distance relay, PSCAD/EMTDC, Power system protection, phasor measurement unit (PMU), static synchronous series compensator (SSSC).

Symbols used in the analysis are as follows

V_p	Voltage at relay location at bus *P*;
I_{p1}	current through faulty line (line1) at relay location at bus *P*;
I_{p2}	current through second line (line2) at relay location at bus *P*;
V_{0p}, V_{1p}, V_{2p}	sequence (zero, positive and negative) phase voltages at relay location at bus *P* respectively;

I_{0p1}, I_{1p1}, I_{2p1}	sequence (zero, positive and negative) phase currents through line 1 at relay location at bus *P* respectively;
I_{0p2}, I_{1p2}, I_{2p2}	Sequence (zero, positive and negative) phase currents through line 2 at relay location at bus *P* respectively;
I_{0q1}, I_{1q1}, I_{2q1}	sequence (zero, positive and negative) phase currents through line 1 at bus *Q* respectively;
V_{0se}, V_{1se}, V_{2se}	sequence (zero, positive and negative) phase voltages at fault location *E* respectively;
V_{0inj}, V_{1inj}, V_{2inj}	Sequence (zero, positive and negative) phase voltages of the SSSC respectively;
R_f	fault resistance;
Z_{0s1}, Z_{1s1}, Z_{2s1}	Sequence (zero, positive and negative) impedances of the line 1 respectively and $Z_{1s1}=Z_{2s1}$.
Z_{0s2}, Z_{1s2}, Z_{2s2}	Sequence (zero, positive and negative) impedances of the line 2 respectively and $Z_{1s2}=Z_{2s2}$.
Z_{0m}	zero sequence mutual impedance between the faulty and second lines;
Z_{0s1}, Z_{1s1}, Z_{2s1}, Z_{0s2}, Z_{1s2}, Z_{2s2}:	Sequence (zero, positive and negative) impedance of source 1 and source 2 respectively.
x	per unit distance from relay point to fault point
x_1	adaptive setting factor

I. INTRODUCTION

Distance protection relays are extensively employed for primary protection in HV transmission lines due to its simplicity and ability to work independent under adverse situations [1, 2]. The fundamental working principle of distance relay is that the line impedance per length is constant. Usually the FACTS Devices are inserted in power lines to improve the power transfer capability and stability limits of system also effects the operation of distance relay in the protection area of power system must be measured and investigated further [3]. SSSC is used to control the power flow, damp out power oscillation and mitigating of sub-synchronous resonance (SSR) in transmission lines [4]. In Ref. [5, 6] the mitigation of SSR is achieved by using FACTS devices with Fractional-order PI controller in the control circuit. The insertion of SSSC in the fault loop affects the components of current and voltage (transient and steady state) [4]. The position and operational modes of SSSC also influences the seen apparent impedance of distance relay.

The consequence of various types of FACTS devices on protection of transmission lines using distance relay have been reported [7-12]. The STATCOM and SVC affects the distance relays with regard to measurement of impedance, operating times, selection of phase and leads to over-reach and under-reach [7, 8].The action of the voltage source converter (VSC) based STATCOM on multiline, increase the resistance to reactance ratio of line, which leads to the impedance relay under-reaching, but no counter measures were not found for zone protection [9, 10]. The work made in [11] provides a fruitful contribution towards the estimation of apparent impedance of distance relay for series devices, viz., TCSC, and SSSC; though, it did not consider the procedure for computing the apparent impedance in case of transmission line consists of series and shunt FACTS controllers. Ref [12-14] addresses the associated problems of shunt/series compensation on distance protection of transmission lines with remedies. Ref [13] presents the apparent impedance calculations for UPFC (unified power flow controller) connected transmission line. The work in Ref. [14] reported the useful techniques to suppress the adverse influence of shunt FACTS on distance protection scheme connected at midway of line, which was implemented in real time digital simulator (RTDS) and suggested improvements to the channel aided distance protection scheme.

Latest communication networks typically use synchronized digital hierarchies (SDH) or synchronized optical network (SONET) standard with communication rates of the order of 155.5 Mb/s, or 274.2 Mbps, respectively [15, 16]. GPS gives time synchronization of the order of $1\mu s$. Time deviation of $1\mu s$ corresponds to a phase error of 0.018^0 for 50 Hz and 0.022^0 for a 60 Hz power system [17]. The work in Ref [18, 19] proposes a synchrophasor state estimator (SynSE) based supervisory system to improve the security of existing scheme. The work in Ref [20] suggests a useful approach to come across the feasible location, where a high-quality of measurement to be addressed to bring the calibration error of all measurements below a predefine threshold. The adaptive current differential protection scheme was proposed in Ref. [21] for transmission line protection in which the error analysis of conventional phasor approach was analysed using the dynamic phasor. If the same time stamped samples of two ends are processed together at one relaying location delay equalizer error can be eliminated [21]. The transfer of instantaneous sampled data between two end synchronized measurements for 200 km line was studied in Ref. [22] and the authors have used the GPS system for data transfer over 100 km of line length.

The principle objective of proposed work in the paper is to mitigate the issues that have been reported in Ref. [23] and Ref. [24] on the adaptive approach of STATCOM and SVC for distance protection schemes to protect transmission lines with midpoint shunt-FACTS compensation, but not given any exact solution for double-circuit transmission line with SSSC. In this research paper, a novel first-zone distance relaying algorithm is proposed for LG fault of parallel lines in presence of SSSC and is reported for the first time. To improve the performance of distance protection without losing its security, first the behaviour of distance relay is analysed through the help of sequence components with SSSC placed at middle of transmission line. The insertion of SSSC adds corresponding impedance in the fault loop, based on the voltage injected by SSSC. The impedance due to SSSC compensates the calculated impedance due to fault at relay point. The error produced by the calculated compensated impedance in the measurement of actual impedance can be nullified at relay point using proposed algorithm with the support of synchronized measurement [25]. The work proposed in Ref. [26-30] is for the single circuit line with SSSC installed on transmission line. The authors mostly proposed the steady state performance-based solutions, which are based on the maximum or minimum compensation injected by SSSC. Because of that, during lower compensation values of SSSC, the relay may under reach or overreach by the relay which is highly undesirable.

In this article the authors have simulated all the possible compensation modes of SSSC and results for modified setting are highly acceptable and outperformed the conventional setting. Also, the settings calculated are stored in the lookup table for quick reference when feedback signal of SSSC compensation reached at relay location, it modifies the setting adaptively. In this current study author have not considered any time lag for data transfer between SSSC and relay, as the distance is almost half of line length with optic fiber communication system. In comparison to the published literature available [26-30], the adaptive setting for varying SSSC compensation and fault trajectory showing the fault response with its behaviour have not been shown by the authors. But in this study, authors have considered all the settings dynamically with the varying compensation and fault trajectory during the fault on the line with various case studies which makes this work different than other published works by various researchers.

The research article is organized as: Section II gives the brief description of the study system model with SSSC. Section III describes the mathematical analysis for apparent impedance of distance protection of double-circuit transmission line with SSSC connected at midway of line. This analysis is more useful in assessing the errors which causes the mal-operation of distance relay. Section IV describes the proposed adaptive mho rely algorithm using PMU. Section V provides the simulation results for adaptive mho relay setting. Section VI concludes the proposed work done fallowed by Appendix A and references.

II. STUDY SYSTEM MODEL WITH SSSC

Figure.1 shows the study system model and control parameters of SSSC. A Bergeron model of double-circuit transmission line, connecting doubly fed generators rating of 100 MVA is simulated using PSCAD. The SSSC is connected at midway of transmission line 1 via an interfacing transformer and distance relay is located at bus *P*. Two 200 km, 500 kV parallel transmission lines terminated with doubly fed with an angle difference of 20^0. The transmission line structural data, parameters of conductor, configuration of tower and source data is provided in Appendix A. PMUs are accessible on relaying and SSSC buses, also a devoted high-speed optical fibre data communication is used for transmission of data.

The SSSC is connected in series with a transmission line1 between buses $B_1$and B_2 shown in Figure 1. The SSSC is modelled by a series connected voltage source in series with impedance; the impedance represents the impedance of interfacing transformer. The block diagram of SSSC control circuit is shown in Figure 2. An instantaneous three-phase set of line voltages, at bus B_1 are used to calculate the reference angle $\theta = \omega t$ and is decoupled into its real component, V_d and reactive component, V_q and then the magnitude, V_{inj} is estimated.

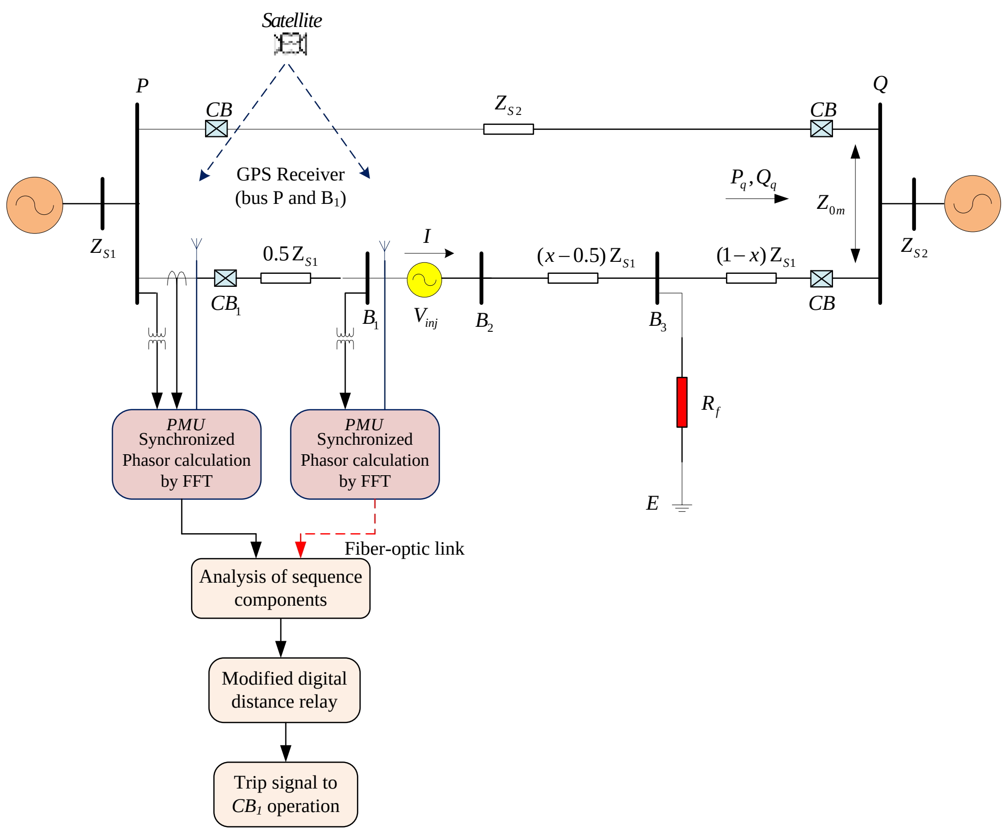


FIGURE 1. One line diagram of study system model.

To control the compensating voltage V_{inj}: compare the absolute value of reference (V_{Ref}) to injected voltage magnitude (V_{inj}) and the error is passed through PI controller acts as a voltage regulator. The PI controller gain is set based on the step response. The output of PI controller is summed to the synchronizing signal ($\theta = \omega t$) as a correction angle ($\Delta\alpha$). The instantaneous measured line currents, I is decoupled into I_d and I_q and then the relative angle of the line current with respect to the phase-lock-loop angle are estimated. The phase shifter determines the reference, V_{Ref} is positive (capacitive) or negative (inductive). Depending on the polarity of $\Delta\alpha$, angle θ and consequently the VSI signals will be advanced or retarded and, thereby the compensating voltage V_{inj} will be shifted with respect to the prevailing line current from its original $\pm\pi/2$ phase position.

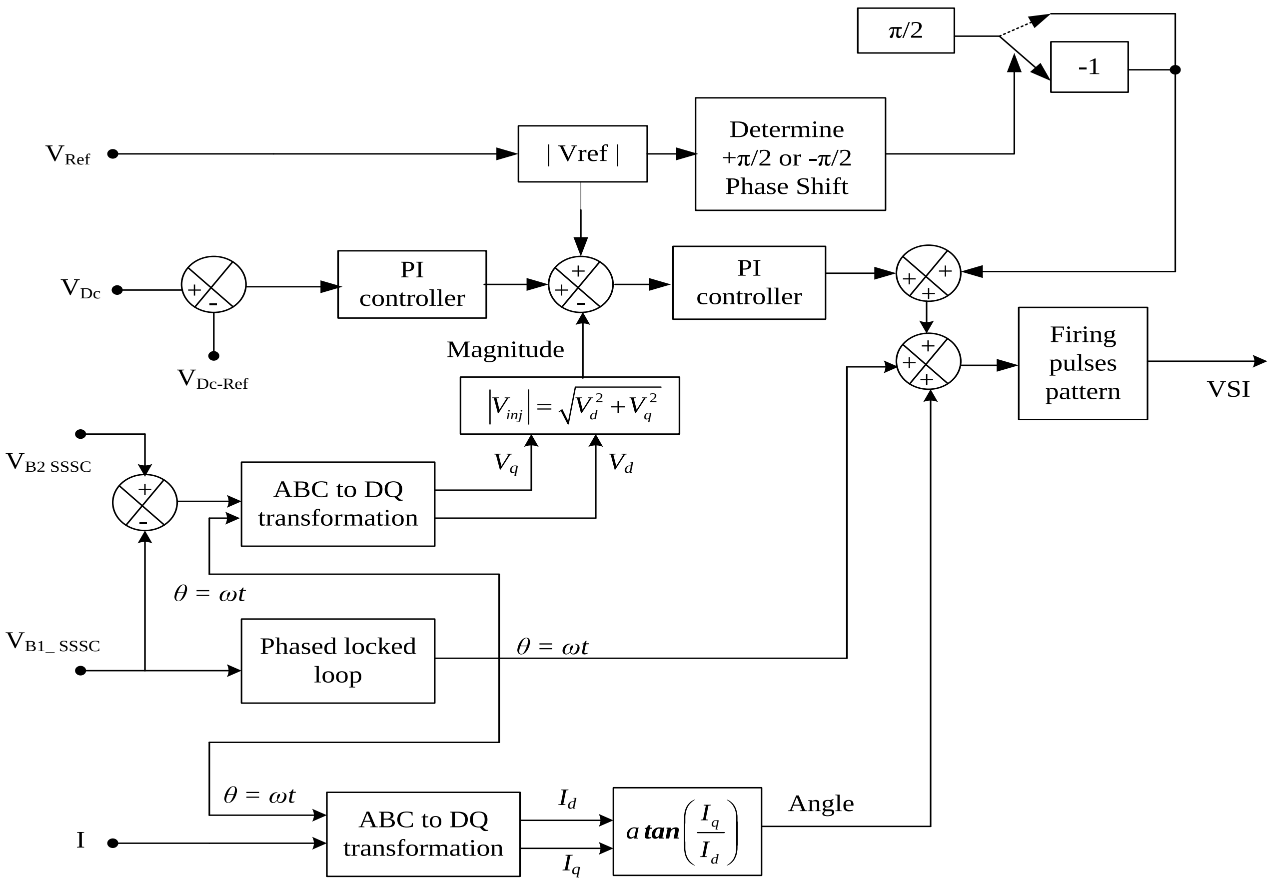


FIGURE 2. Block diagram of SSSC control circuit.

III. APPARENT IMPEDANCE ANALYSIS WITH MID-POINT SSSC

A dual fed double-circuit transmission line having SSSC at centre of the transmission line1 subjected to a single line to ground (SLG) fault and is shown in Figure 3.

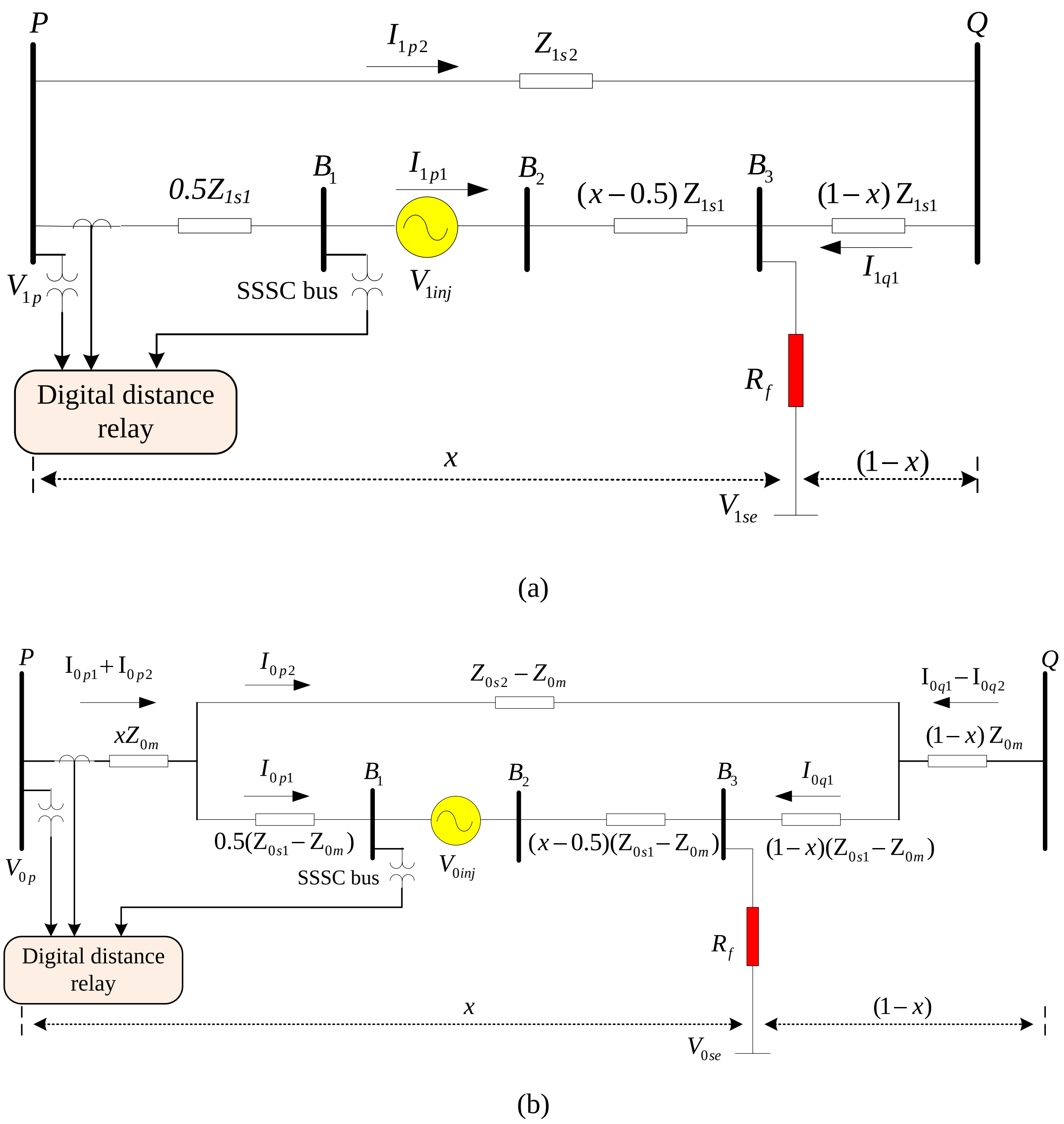


FIGURE 3. Simplified circuit of study system with SSSC; a) positive sequence network b) zero sequence network.

If SLG fault occurs on the right side of the SSSC at distance is x from the relay point, the zero sequence and positive networks of the study system during the fault are shown in Figure 3(a) and Figure 3(b) respectively.

The following equations can be derived for lines1and 2 for fault bus B_3 with a fault resistance R_f from the positive sequence network according to Figure 3 (a),

$$V_{1p} = xZ_{1s1}I_{1p1} + R_f(I_{1p1} + I_{1q1}) + V_{1inj} + V_{1se} \quad (1)$$

$$V_{1p} = Z_{1s2}I_{1p2} + (1-x)Z_{1s1}I_{1q1} + R_f(I_{1p1} + I_{1q1}) + V_{1se} \quad (2)$$

By eliminating the term $V_{1se}$from equations (1) and (2), the following equation is obtained:

$$I_{1q1} = \frac{xI_{1p1}}{1-x} + \frac{V_{1inj}}{(1-x)Z_{1s1}} - \frac{k_1 I_{1p2}}{(1-x)} \quad (3)$$

where, $k_1 = Z_{1s2} / Z_{1s1}$ (4)

By substituting equation (3) in (1), the following equation is obtained:

$$V_{1p} = xZ_{1s1}I_{1p1} + V_{1inj} + V_{1se} + \frac{R_f}{(1-x)}\left(I_{1p1} - k_1 I_{1p2} + \frac{V_{1inj}}{Z_{1s1}} \right) \quad (5)$$

Negative sequence voltage expression is given by

$$V_{2p} = xZ_{1s1}I_{2p1} + R_f(I_{2p1} + I_{2q1}) + V_{2inj} + V_{2se} \quad (6)$$

$$V_{2p} = Z_{1s2}I_{2p2} + (1-x)Z_{1s1}I_{2q1} + R_f(I_{2p1} + I_{2q1}) + V_{2se} \quad (7)$$

By eliminating terms containing I_{2q1}, from (6) and (7), the following equation is obtained:

$$V_{2p} = xZ_{1s1}I_{2p1} + V_{2inj} + V_{2se} + \frac{R_f}{(1-x)}\left(I_{2p1} - k_1 I_{2p2} + \frac{V_{2inj}}{Z_{1s1}} \right) \quad (8)$$

From the zero sequence e networks according to Figure 3(b), the following equations can be derived:

$$V_{0p} = x(Z_{0m}I_{0p2} + Z_{0s1}I_{0p1}) + R_f(I_{0p1} + I_{0q1}) + V_{0inj} + V_{0se} \quad (9)$$

$$V_{0p} = xZ_{0m}(I_{0p2} + I_{0p1}) + (Z_{0s2} + Z_{0m})I_{0p2} + (Z_{0s1} - Z_{0m})(1-x)I_{0q1} + R_f(I_{0p1} + I_{0q1}) + V_{0se} \quad (10)$$

By eliminating terms containing I_{0q1}, from equations (9) and (10), the following is obtained:

$$V_{0p} = x(Z_{0m}I_{0p2} + Z_{0s1}I_{0p1}) + V_{0inj} + V_{0se} + \frac{R_f}{(1-x)}\left(I_{0p1} - k_0 I_{0p2} + \frac{V_{0inj}}{(1-x)(Z_{0s1} - Z_{0m})} \right) \quad (11)$$

where, $k_0 = (Z_{0s2} - Z_{0m}) / (Z_{0s} - Z_{0m})$ (12)

By taking identical parameters for parallel lines, $k_1 = k_0 = 1$.

A. SLG Fault

For an AG fault, the boundary condition is;

$$V_{0se} + V_{1se} + V_{2se} = 0 \tag{13}$$

From equations (1), (5), (6) and (8), the relay point voltage can be derived as;

$$V_p = xZ_{1s1}I_{p1} + x(Z_{0s1} - Z_{1s1})I_{0p1} + xZ_{0m}I_{0p2} + V_{inj} + \frac{R_f}{(1-x)}\left(\begin{array}{l} I_{p1} - k_1 I_{p1} + (k_1 - k_0)I_{0p2} + \\ \dfrac{V_{inj}}{Z_{1s1}} + V_{0inj}(\dfrac{1}{(Z_{0s1} - Z_{0m})} - \dfrac{1}{Z_{1s1}} \end{array}\right) \tag{14}$$

where,
$$\begin{aligned} V_{0p1} + V_{1p1} + V_{2p1} &= V_p \\ I_{0p1} + I_{1p1} + I_{2p1} &= I_{p1} \\ I_{0p2} + I_{1p2} + I_{2p2} &= I_{p2} \\ V_{0inj} + V_{1inj} + V_{2inj} &= V_{inj} \end{aligned} \tag{15}$$

The apparent impedance of distance relay without SSSC for a single phase to ground fault, can be calculated using the equation:

$$Z = \frac{V_p}{I_{p1} + mI_{0p1}} = \frac{V_p}{I_{\mathrm{Re}lay}} \tag{16}$$

where, m is compensation factor for zero sequence current, i.e. $m = Z_{0s1} - Z_{1s1}/Z_{1s1}$

The apparent impedance seen by this relay (conventional) with SSSC can be expressed as

$$Z = Z_{app} = xZ_{1s1} + xZ_{0m}\frac{I_{0p2}}{I_{\mathrm{Re}lay}} + \frac{R_f}{(1-x)I_{\mathrm{Re}lay}}(I_{p1} - k_1 I_{p2} + (k_1 - k_2)I_{0p2}) + \Delta Z \tag{17}$$

where,
$$\Delta Z = \frac{V_{inj}}{I_{\mathrm{Re}lay}} + \frac{R_f}{(1-x)I_{\mathrm{Re}lay}}\left(\frac{V_{inj}}{Z_{1s1}} + V_{0inj}\frac{1}{(Z_{0s1} - Z_{0m})} - \frac{1}{Z_{1s1}}\right) \tag{18}$$

From equation (17), in absence of SSSC, ΔZ is zero and the apparent impedance is the same as uncompensated lines. From equation (18), with midpoint SSSC placed at one of the double-circuit transmission line, apparent impedance expression comprises a new factor with series injected voltage (V_{inj}) as the prime contributing component. Due to this new factor the apparent impedance computed by distance relay is erroneous and mal-operate to locate the fault point.

B. Line to Line Fault (LL)

For an AB fault, the boundary condition is:

$$V_{1se} = aV_{2se} \tag{19}$$

where; a = - 0.5- j0.866

From equations (4), (6) and (19) we have obtaining final equation of phase to phase fault with SSSC given by

$$Z = Z_{app} = xZ_{1s1} + xZ_{0m}\frac{I_{0p2}}{I_{Relay}} + \frac{R_f}{(1-x)I_{Relay}}\left(I_{1p1} - aI_{2p1}\right) + k_1\left(aI_{2p2} - I_{1p2}\right) + \Delta Z \tag{20}$$

In above equation, ΔZ depends on SSSC and it is equal to;

$$\Delta Z = \frac{V_{inj} - aV_{2inj}}{I_{Relay}} + \frac{R_f}{(1-x)I_{Relay}}\left(\frac{V_{1inj} - aV_{2inj}}{Z_{1s1}}\right) \tag{21}$$

In above equation R_f is the fault resistance between two phases. According to equation (21) for R_f= 0, SSSC is due to the negative and positive sequence voltage differences. Thus, three phase fault measuring units can cater for all the seven-faults, in similar procedure given for apparent impedance calculation for LL fault.

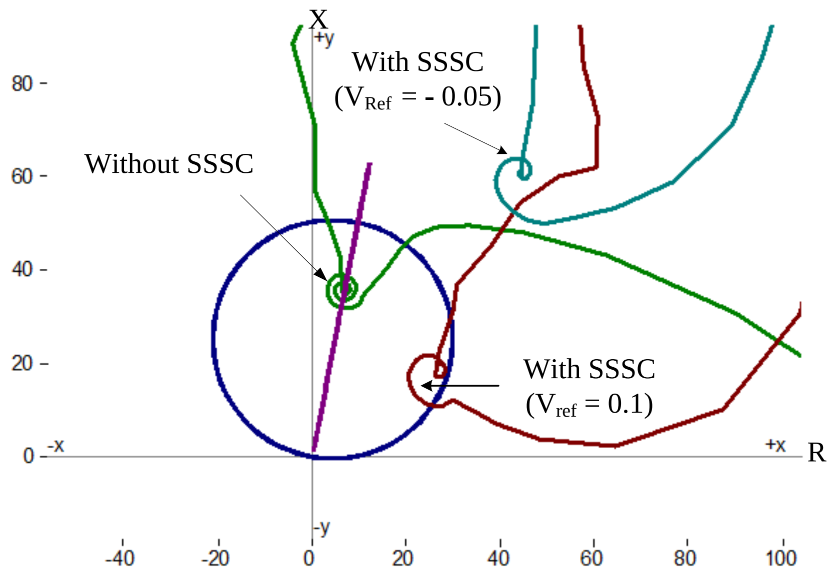


FIGURE 4. Seen Impedance by Mho relay (SLG fault & with/without midpoint SSSC) for various SSSC setting (fault location is 140 km and R_f= 20 ohm).

The impact of internal setting of SSSC on the performance of distance relay, for an SLG fault is shown in Figure 4. Further, the seen apparent impedance of distance relay without and with SSSC have been obtained and compared for various values of reference voltages (V_{Ref}) of SSSC.

Without SSSC the relay recognizes the exact impedance value and then enters to the first zone (green colour). Figure 4 shows the effect of different working modes of SSSC with relay trajectory. As it can be clearly shown that for SSSC setting values of -0.05 (teal colour) and 0.1 p.u. (magenta colour) the relay is under reaches.

IV. PROPOSED ADAPTIVE MHO RELAY ALGORITHM

A. Modified First Zone Setting of distance relay

The prime objective of the proposed research work is to design an adaptive algorithm for distance protection in presence of SSSC at mid-point of transmission line. The research objective is achieved by making necessary modifications in the calculation of apparent impedance formula, which is in equation (17). Equation (17) compares with relay setting (Z_{set}) of first zone to take the exact decision of no trip or trip during fault in the protected zone. By equating the apparent impedance calculated in equation (17) to setting of distance relay which is 80% (160 km) of line1.

$$Z_{app} = Z_{set} = 0.8Z_{line1} = 0.8Z_{1s1} \tag{22}$$

Comparing equation (17) and (22), we get

$$0.8Z_{1s1} = xZ_{1s1} + xZ_{0m}\frac{I_{0p2}}{I_{\mathrm{Re}lay}} + \frac{R_f}{(1-x)I_{\mathrm{Re}lay}}(I_{p1} - k_1 I_{p2} + (k_1 - k_2)I_{0p2}) + \Delta Z \tag{23}$$

Considering R_f=0, the right half term of equation (23) can be eliminated and after making necessary changes in equation (23) can be rewritten as

$$0.8Z_{1s1} = xZ_{1s1} + xZ_{0m}\frac{I_{0p2}}{I_{\mathrm{Re}lay}} + \frac{V_{inj}}{I_{\mathrm{Re}lay}} \tag{24}$$

Equation (24) can be rewritten as

$$0.8Z_{1s1} = x(Z_{1s1} + Z_{0m}\frac{I_{0p2}}{I_{\mathrm{Re}lay}}) + \frac{V_{inj}}{I_{\mathrm{Re}lay}} \tag{25}$$

$$x_1 = 0.8Z_{1s1} - \left(\frac{V_{inj}}{I_{\mathrm{Re}lay}Z_{1s1}}\right) + Z_{0m}\left(\frac{I_{\mathrm{Re}lay}}{I_{0p2}}\right) \tag{26}$$

where, x is becomes x_1 and noted as adaptive setting factor. With the modified setting, the adaptive distance protection will ensure the computed apparent impedance (Z_{app}) and take the decision of tripping presence of mid-point SSSC in the transmission line. And hence to obtain the modified setting, multiply equation (26) with Z_{line1}.

$$Z_{setnew} = xZ_{1s1} = x_1 Z_{line1} \tag{27}$$

Multiplying equation (26) with Z_{line1} and substituting in (27), we get

$$Z_{setnew} = \left[0.8Z_{1s1} - \left(\frac{V_{inj}}{I_{Relay} Z_{1s1}} \right) + Z_{0m} \left(\frac{I_{Relay}}{I_{0p2}} \right) \right] Z_{line1} \tag{28}$$

From the above equation, the fallowing interpretations are made: If SSSC injects capacitive compensation then adaptive zone increased while for inductive compensation adaptive zone is decreased. Depending on the compensation level the proposed adaptive distance protection setting automatically adjusts the reach of first zone. With nature of injected voltage, the proposed adaptive distance protection zone setting value is automatically adjusted. Injected voltage will affect the calculation of apparent impedance with fault after SSSC. Further the location of SSSC also affects the calculation of apparent impedance.

B. Proposed Adaptive Mho Relay Algorithm

Flowchart given in Figure5 clearly explains the operation of proposed Adaptive Mho relay algorithm with SSSC. In this the modification of conventional Mho relay algorithm is done using the information of PMU measurements.

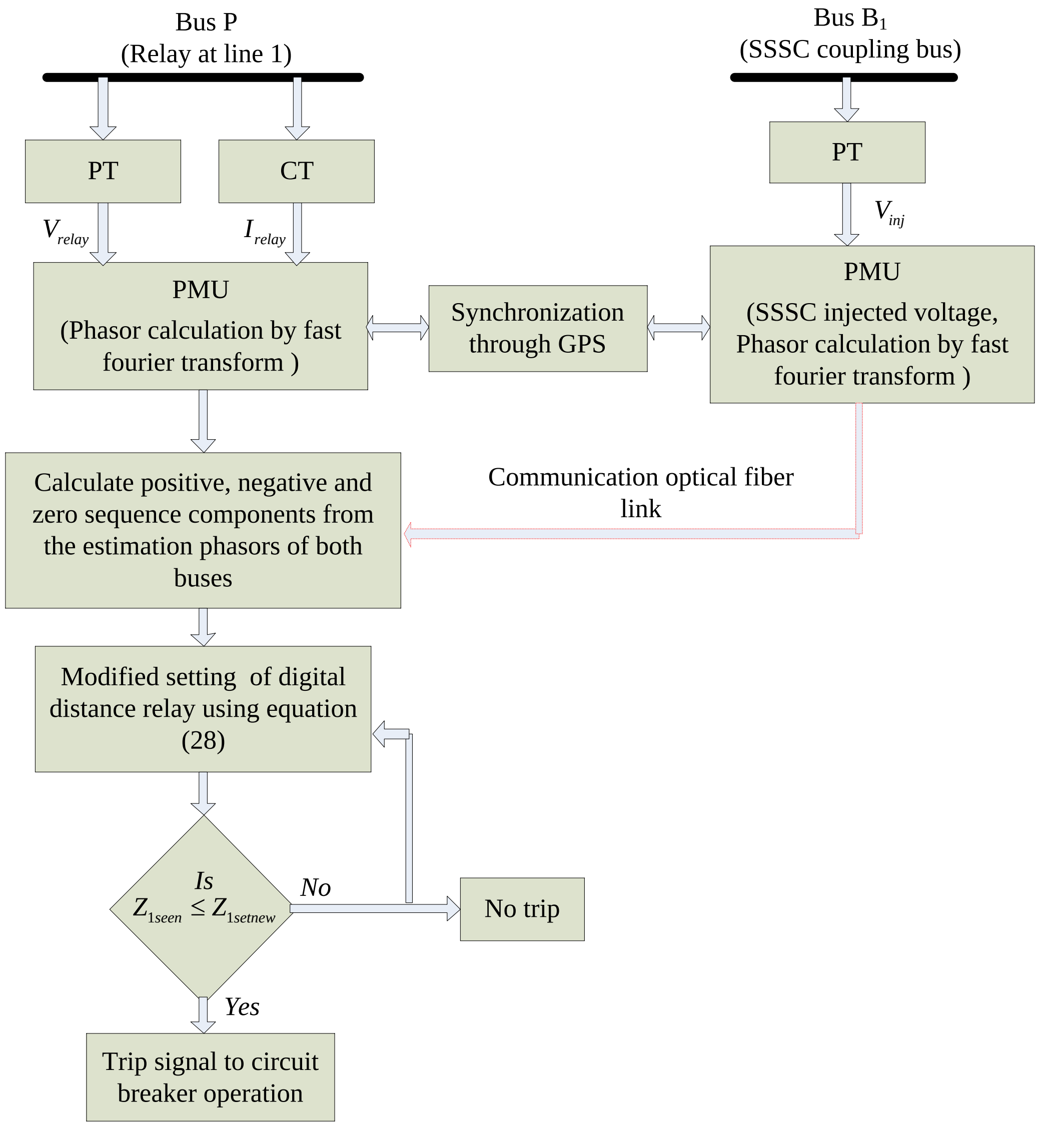


FIGURE 5. Adaptive algorithm of digital distance relaying.

The Mho relay is set to protect 80% of the transmission line 1 and is placed at sending-end bus *P*. The Mho relay at relay bus *P* monitors the line current (I_s) and phase voltage (V_s) with the help of current transformer (CT) and potential transformer (PT). The SSSC is placed at coupling bus B_1, which is 100 km from the sending-end generator of line 1. Injected voltage V_{inj} by SSSC is measured at bus B_1 and the same measurements is transmitted through a fiber-optic communication channel to bus *P* and further it is fed to the adaptive setting relay unit.

V. SIMULATION RESULTS

To investigate the effectiveness of modified distance protection (adaptive), the system shown in Fig.1, is simulated using PSCAD/EMTDC software (Manitoba HVDC Research Centre, Winnipeg, Manitoba, Canada) [25]. By using load-flow analysis the voltage magnitude and load angles of generator are calculated. The 48-pulse dynamic model of SSSC is used. To estimate the adaptive first zone settings of distance, rely, control over the setting value of SSSC i.e. V_{Ref} is set between ± 0.1p.u. The positive value of V_{ref} indicates capacitive compensation and negative value indicate inductive compensation.

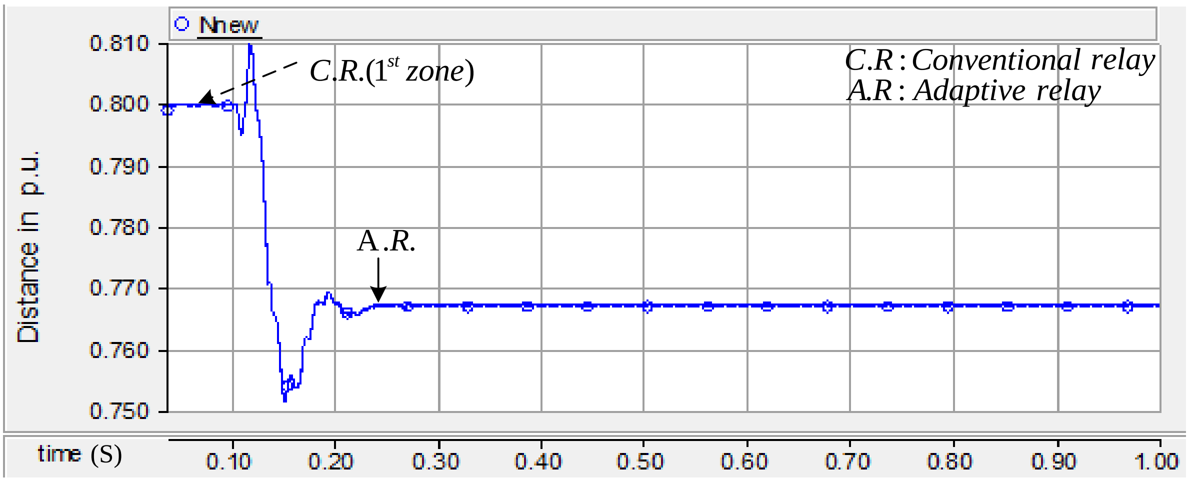


FIGURE 6. Adaptive distance setting factor x_1 with SSSC setting value V_{Ref} = -0.1 p.u., with forward power flow.

The SSSC connected at mid-point gets into action at 0.1 sec. The voltage at mid-point is decreases with the absorption of Inductive reactive power by SSSC as compared to the usual working voltage with no SSSC. This leads the reduction in relay voltage of bus and further a decrease in seen apparent impedance of distance relay causing over-reach. The simulation result of Adaptive distance relay with SSSC setting value V_{Ref} = -0.1 p.u., the setting factor x_1 is shown in Figure 6 for forward power flow (power flow direction from bus *P* to bus *Q*).

When SSSC is connected at 0.1 sec into the system and absorbs reactive power of inductive, the setting factor x_1 is is decreased adaptively and it settles to 0.7671 p.u. distance value by taking 12 milliseconds to get a new first zone adaptive setting. This new adaptive setting factor is used to define dynamic mho distance relay reach as shown in Figure 7. It is observed that for SSSC setting value V_{Ref} = -0.1 p.u., adaptive relay reach is reduced (green colour) as compared to conventional relay reach (red colour).

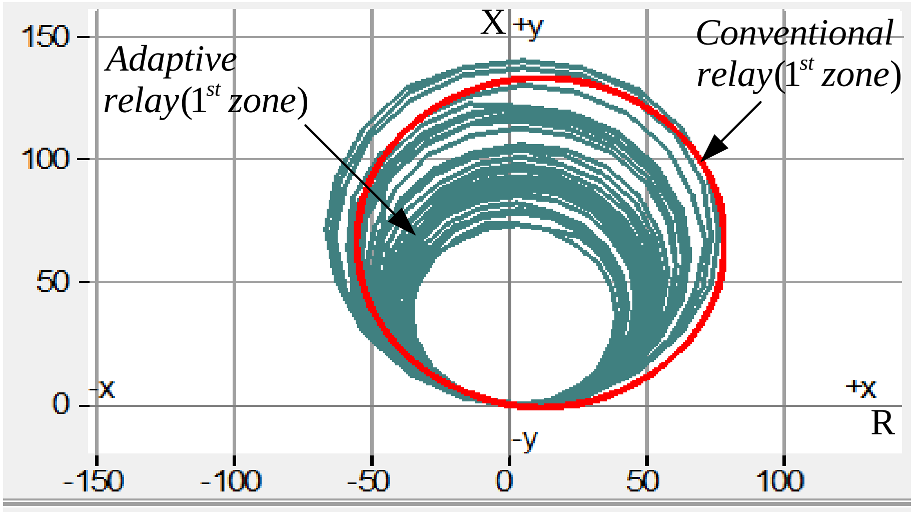


FIGURE 7. Conventional versus adaptive mho relay characteristics with SSSC setting value V_{Ref} = -0.1 p.u. with forward power flow.

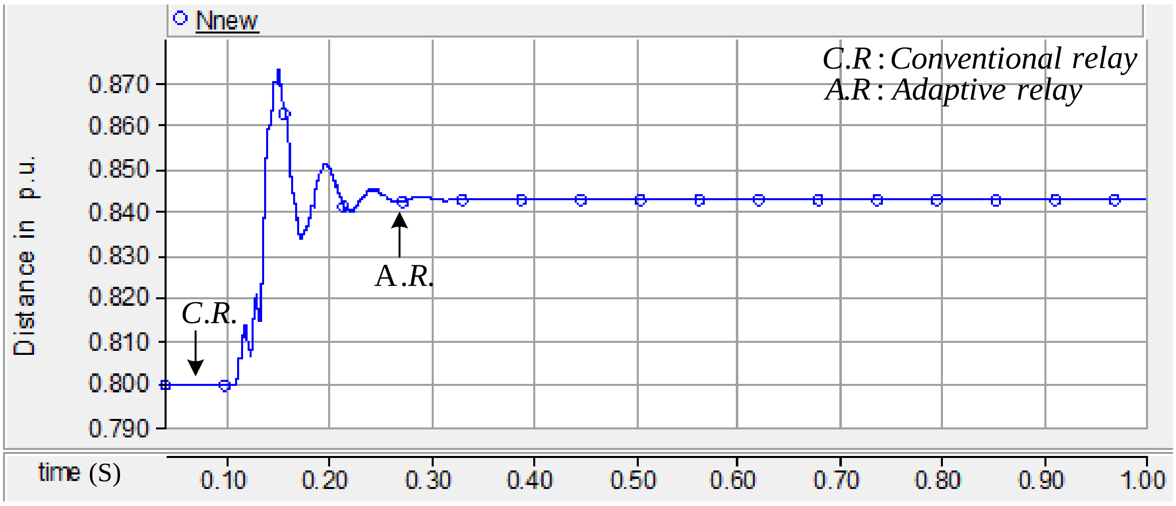


FIGURE 8. Adaptive distance setting factor $x_1$with SSSC setting value V_{Ref}= 0.1 p.u. with forward power flow.

When SSSC setting value is V_{Ref}= 0.1 p.u., there is an increase in voltage at mid-point as compared to voltage under usual operating condition without SSSC. Subsequently the relaying voltage of bus and the seen apparent impedance of distance relay also increase and leads to under-reach. The adaptive relay setting factor $x_1$obtained for V_{Ref} = 0.1 p.u. into the system is shown in Figure 8 for forward power flow. The setting factor of relay is 0.8 without SSSC and is adaptively increases to 0.8425 per unit distance value with SSSC by taking 25 milliseconds to settle shown in Figure 8.

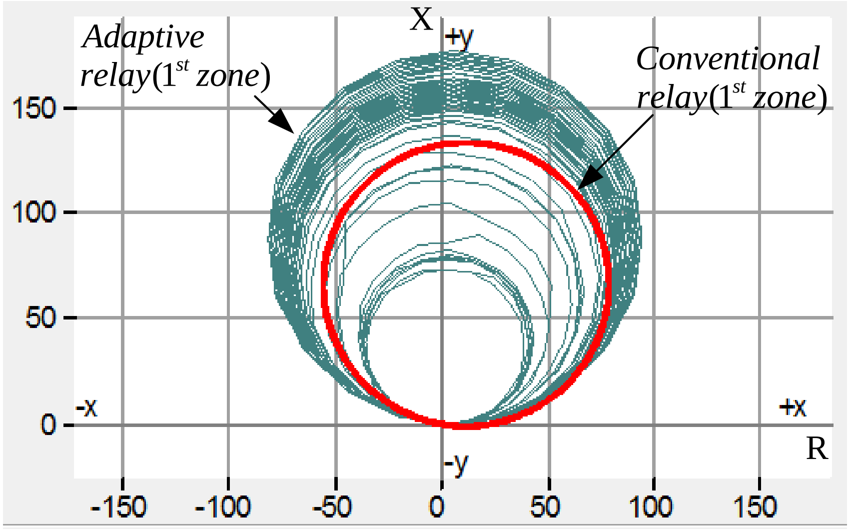


FIGURE 9. Conventional versus adaptive mho relay characteristics with SSSC setting value V_{Ref} = 0.1 p.u. with forward power flow.

Figure9 shows the conventional relay reach (red colour) and adaptive mho relay reach (green colour). It is seen that for SSSC setting value V_{Ref} = 0.1 p.u., the reach of relay is increased adaptively as compared to conventional relay reach. In the same way, conclusion is drawn from Figures8-11 with the injection of capacitive and inductive reactive power by SSSC to make distance relay setting factor adaptive. The adaptive setting factor x_1 requires a less time to settle (approximately one and half cycle) for V_{Ref} = - 0.1 p.u., and around three cycle to get settle for V_{Ref} = 0.1 p.u. It is because of the use of PI controller and is having its own settling time constant which is represented in modelling of SSSC in the paper.

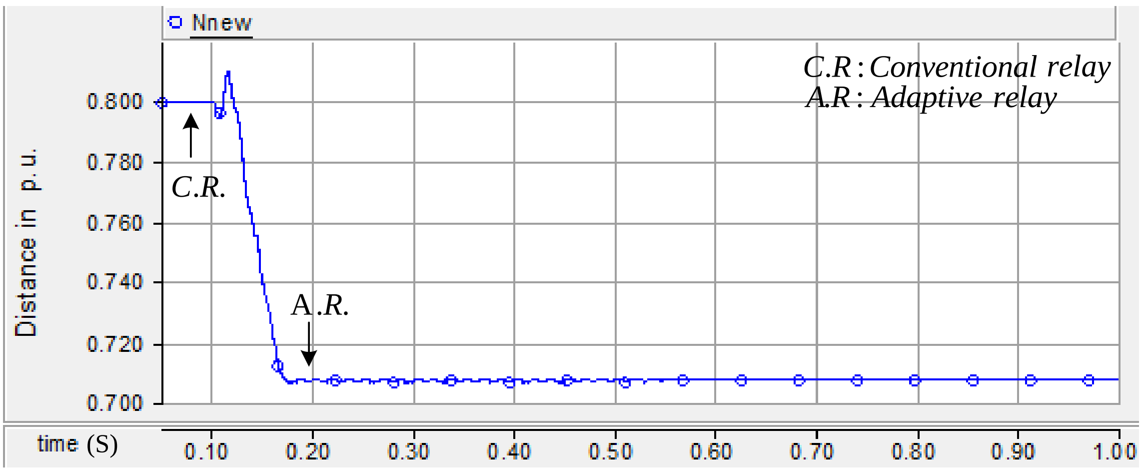


FIGURE 10. Adaptive distance setting factor x_1 with SSSC setting value V_{Ref}= - 0.1 p.u., with reverse power flow.

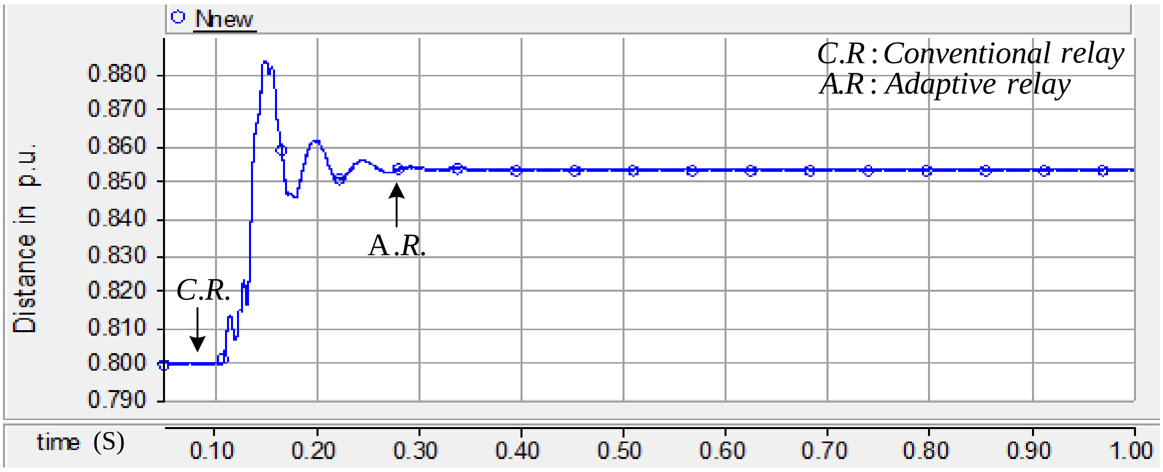


FIGURE 11. Adaptive distance setting factor x_1 with SSSC setting value V_{Ref}= 0.1 p.u., with reverse power flow.

Figure 12 shows the variation of adaptive setting factor with change in SSSC reference voltage V_{Ref} in the step of 0.01 p. u. The capacitive reactive power injection is represented by positive value and the inductive reactive power absorption represented by negative value. When SSSC is in inactive mode and the system neither absorbs nor injects any power (reactive) and the observed setting factor is 0.7956. This is due to the reactance of interfacing transformer of 0.1 per unit which comes into the circuit. For flow of power in forward direction from P to Q, adaptive setting factor for first zone is 0.8425 and 0.7671 per unit distance for V_{Ref} = 0.1 p.u., and V_{Ref} = - 0.1 p.u., respectively as shown in Figure 12.

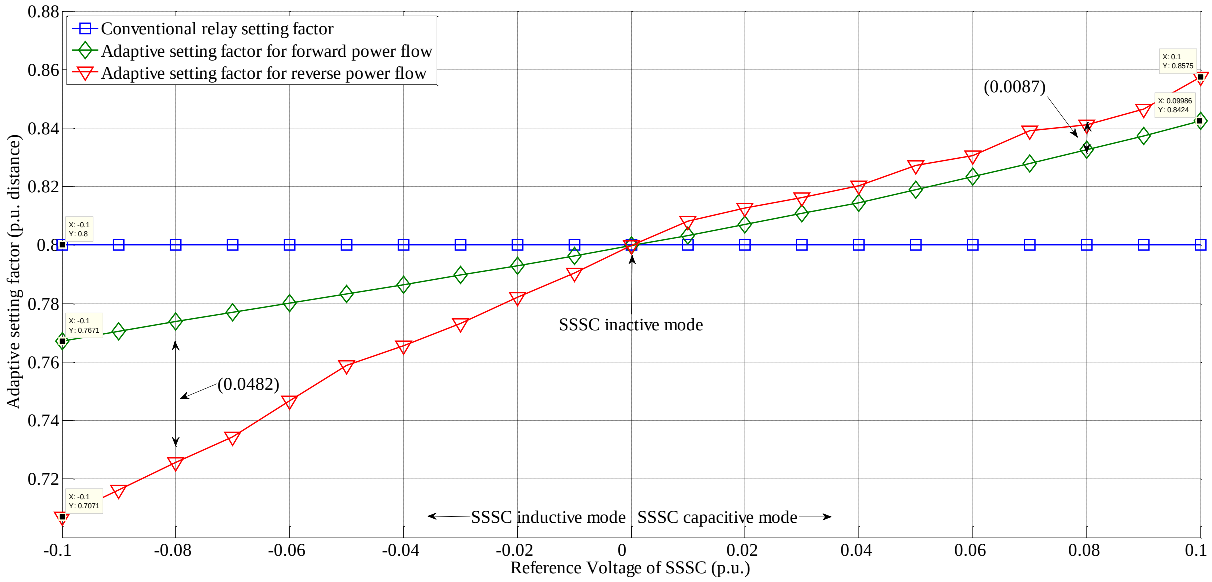


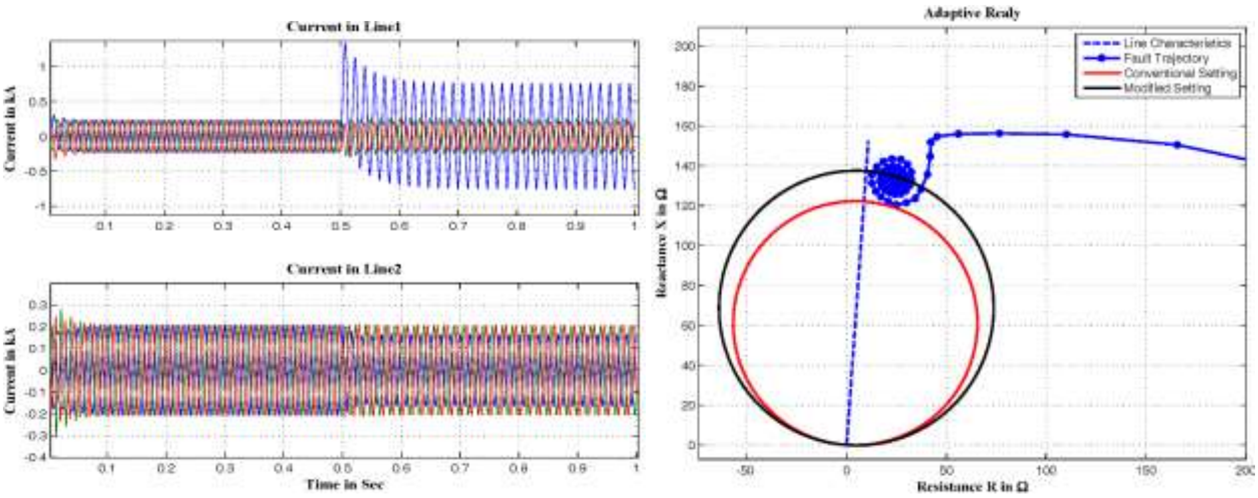
FIGURE 12. Adaptive setting factor of distance relay verses reference voltage of SSSC.

Results obtained from simulation show the fallowing observations and are as follows-

i. Adaptive setting factor for SSSC setting value, V_{Ref}= -0.1 p.u in forward power flow is 0.7671 p.u. distance which is more than the setting factor in reverse power flow of 0.7071 p.u distance. This is because of distance relay is connected at bus *P* of line 1.
ii. For SSSC setting value, V_{Ref} = 0.1 p.u in forward power flow is 0.8425 p.u. distance which is lesser than the reverse power flow 0.8575 p.u. distance.
iii. Also, it is clear from the above figure that variation of SSSC reference voltage in reverse power flow, the adaptive setting factor difference is more as compare to forward power flow.
iv. From Figures7 and 9 the time taken to reach new adaptive setting is different because it depends on capacitive/inductive compensation mode also settling time of PI controller and interfacing transformer of SSSC.

VI. CASE STUDIES

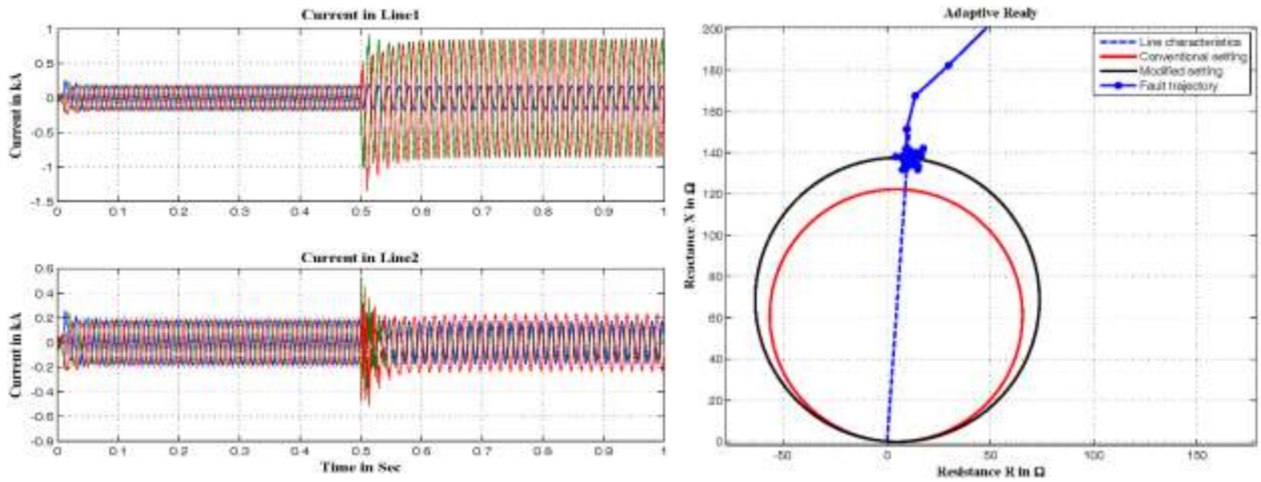
A. Parallel operation of both the lines



(a) (b)

Figure 13. Ag Fault response with SSSC (V_{ref}=0.1) for parallel operation fault at 80 % of line-1 (a) Line currents in both lines (b) Mho characteristics with conventional and modified setting

Figure 13 shows the response for ling to ground fault (Ag) and figure 14 show the response for line to line fault (BC) with SSSC for parallel operation of both lines with relay is considered on line-1. The current waveforms for both the fault conditions are shown in the figure 13 (a) and figure 14 (a) and Mho characteristics of conventional setting and modified setting in presence of SSSC with fault trajectory is shown in figure 13 (b) and figure 14 (b). In the case of parallel line operation, both the line is connected when fault occurred at 0.5 sec and to see the performance of the relay response, the fault is kept sustained. The effect of faults on other line can be observed in the figures. The modified relay outperforms the conventional relay near the boundary condition for both faults.



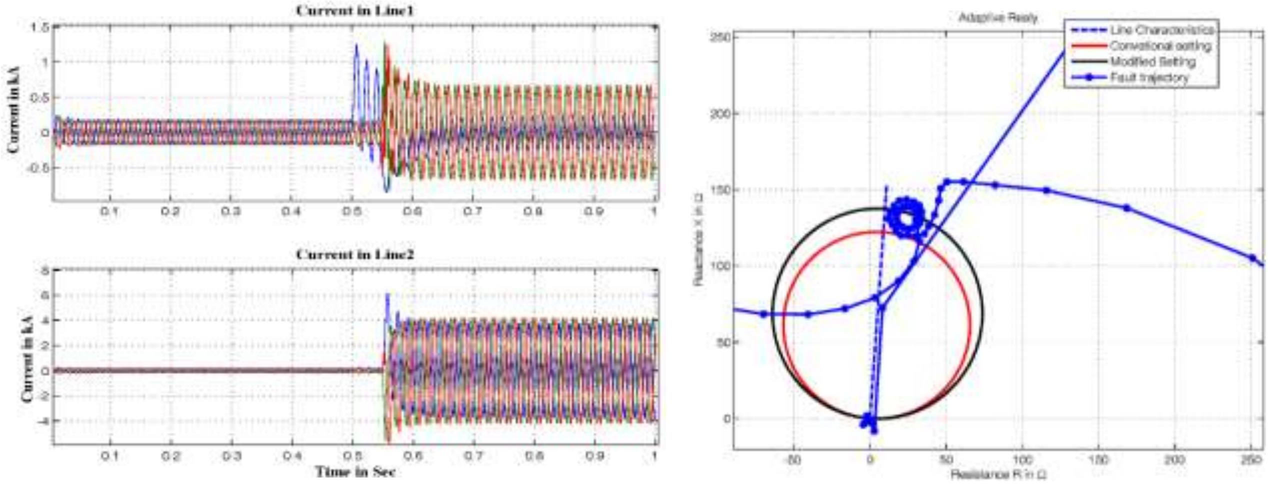
(a) (b)

Figure 14. BC Fault response with SSSC (V_{ref}=0.1) for parallel operation fault at 80 % of line-1 (a) Line currents in both lines (b) Mho characteristics with conventional and modified setting

Figure 15 (a) show the fault currents in both lines for line to ground fault, when line-2 is grounded at (0.6 sec) during fault on line-1 (0.5 sec). The modified and conventional setting with fault trajectory is shown in figure 15 (b). The line-2 is grounded near to the sending end bus. The fault trajectory first enters the modified setting and when line-2 is grounded, it oscillates for 1 or 2 cycle, leaving the modified setting. After few cycle of oscillations, the fault trajectory resides at zero impedance value which can be observe in figure 15 (b).

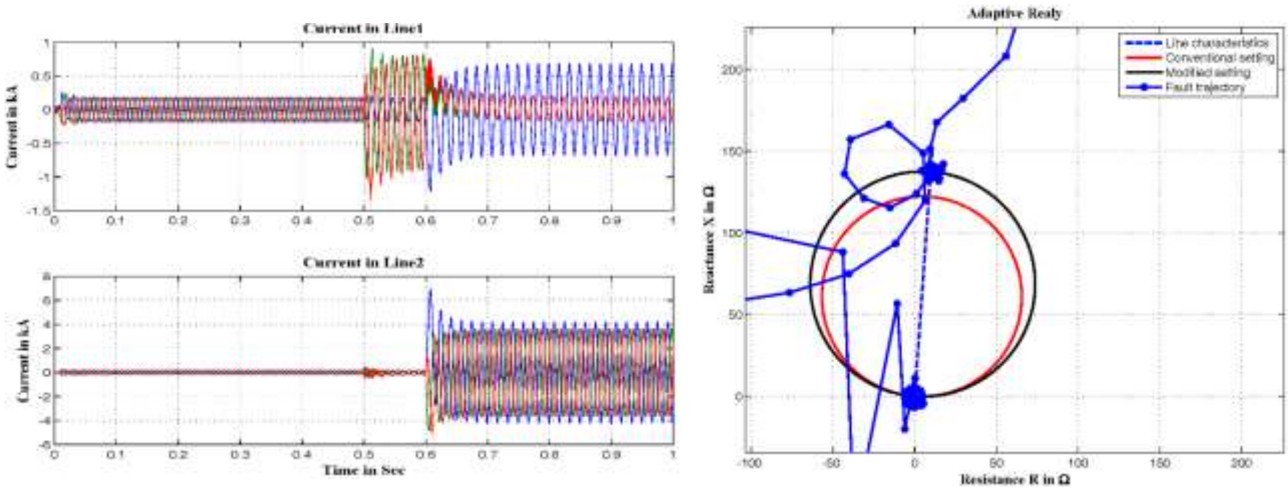
For line to line fault the line currents in both lines is shown in figure 16 (a) when fault on line-1 occur at 0.5 sec and line-2 is grounded at 0.6 sec. Figure 16 (b) shows the fault trajectory with modified and conventional settings. The fault trajectory shows variation in its response due to SSSC compensation which settles on the boundary of modified setting. When line-2 is grounded, the fault trajectory moves out of the both the relay setting due to oscillations and finally settled at zero impedance value. In this case of line-2 grounded in the interval of 5 cycles, the modified relay accurately detects the both faults.

B. One line grounded



(a) (b)

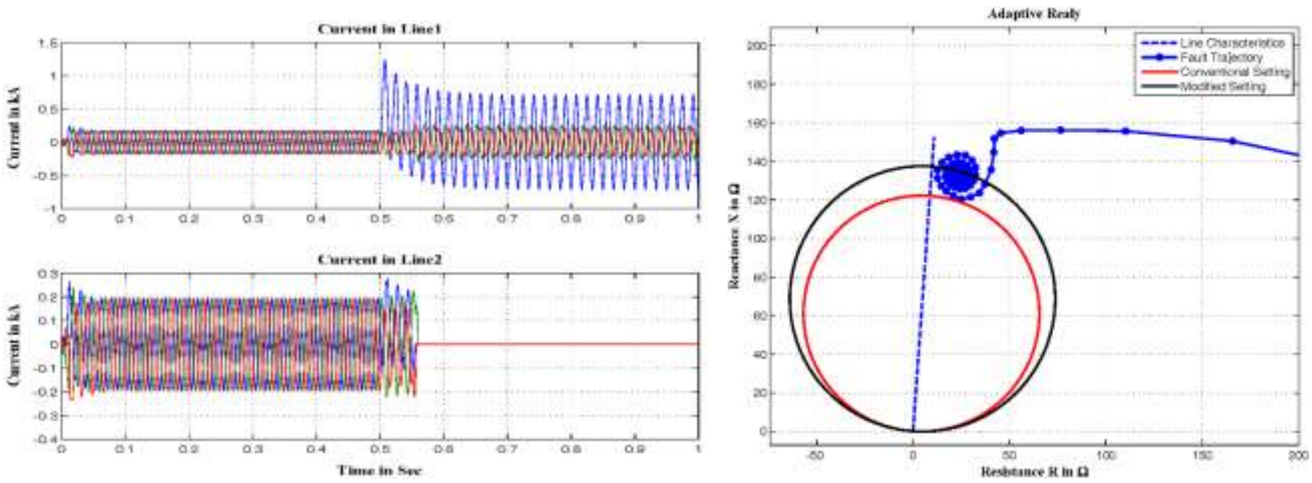
Figure 15. Ag Fault response with SSSC (V_{ref}=0.1) for line2 grounded at 0.55sec (a) Line currents in both lines (b) Mho characteristics with conventional and modified setting



(a) (b)

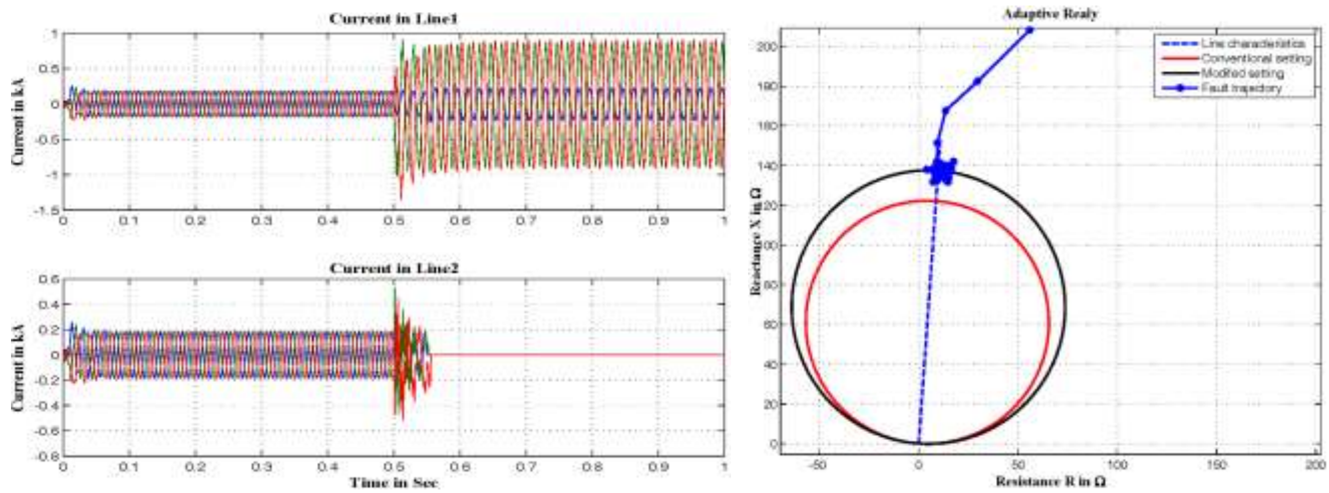
Figure16. BC Fault response with SSSC (V_{ref} = 0.1) for line2 grounded at 0.60sec for fault at 80 % of line1 (a) Line currents in both lines (b) Mho characteristics with conventional and modified setting

C. *One line opened*



(a) (b)

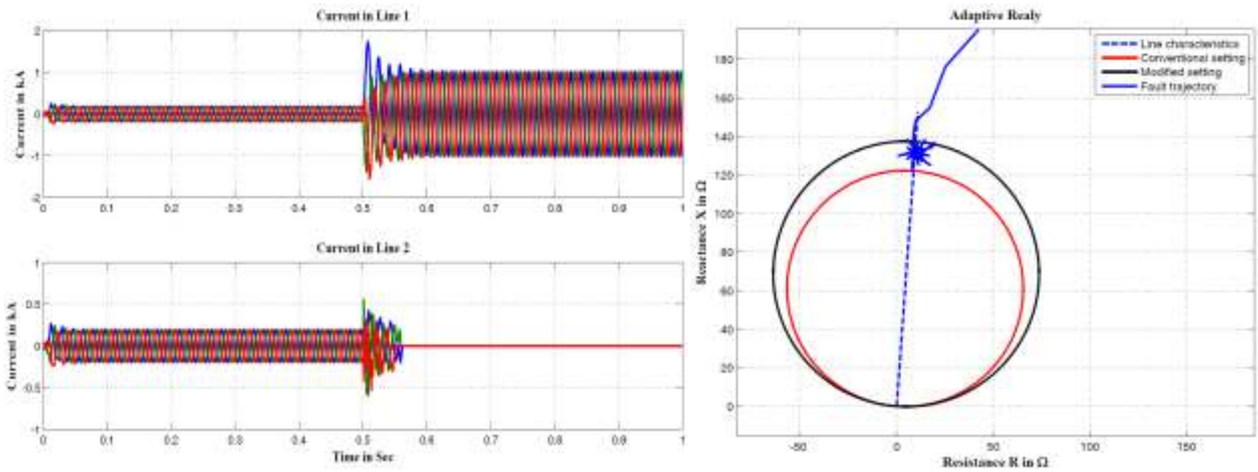
Figure 17. Ag Fault response with SSSC (V_{ref}=0.1) for line2 opened at 0.55sec (a) Line currents in both lines (b) Mho characteristics with conventional and modified setting



(a) (b)

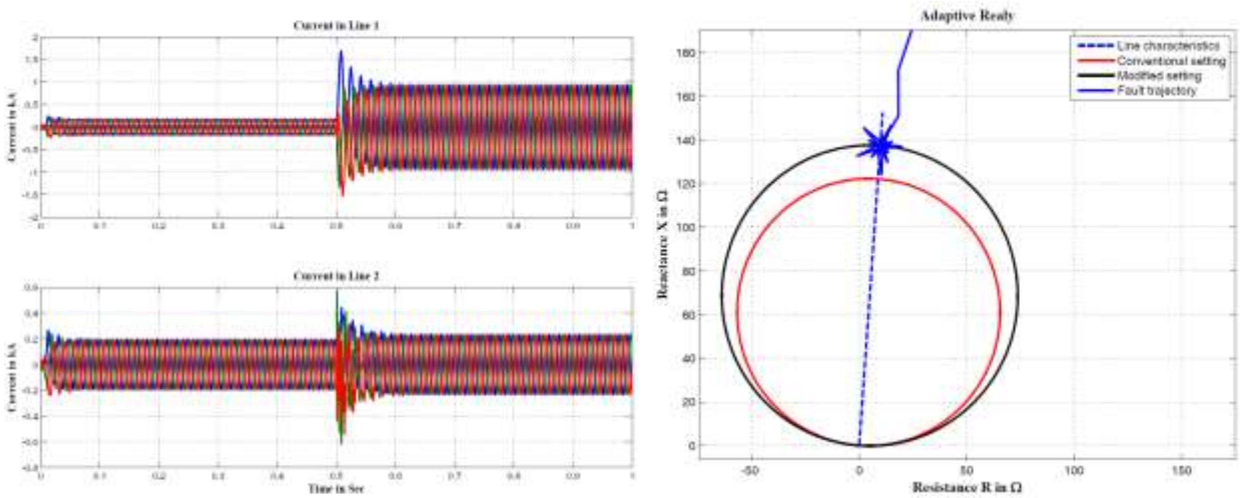
Figure 18. BC Fault response with SSSC (V_{ref}=0.1) for line2 opened at 0.55sec (a) Line currents in both lines (b) Mho characteristics with conventional and modified setting

In this case the line-2 is opened at 0.55 sec when fault is occurred on line-1 at 0.5 sec. The line currents waveforms for line to ground and line to line faults are shown in figures 17 (a) and 18 (a) respectively. Fault trajectory for both faults with modified and conventional settings are shown in figure 17 (b) and figure 18 (b). It is observed from the line current waveforms that, when line-2 got opened, the currents in the line-1 increased, but the effect on currents which is subjected to fault is not that much prominent as compared to other phases which are healthy. The fault trajectory for line to line fault have small deviation which can be observed in figure 18 (b), but it gets settled within 1 cycle giving accurate detection of fault. Similar results are observed for three phase fault on line-1 when line-2 was opened in figure 19 for fault at 70% of line length and when both lines operating in figure 20 for fault at 80% of line length.



(a) (b)

Figure 19. ABC Fault response with SSSC (V_{ref}=0.1) for line2 opened at 0.55sec for fault at 70 % of line1 (a) Line currents in both lines (b) Mho characteristics with conventional and modified setting



(a) (b)

Figure 20. ABC Fault response with SSSC (V_{ref}=0.1) for fault at 80 % of line1 (a) Line currents in both lines (b) Mho characteristics with conventional and modified setting

D. *Comparative discussion*

The above discussed case study for three conditions is performed using the fixed SSSC compensation. In the study, authors have simulated all the possible compensation modes of SSSC and results for modified setting are highly acceptable and outperformed the conventional setting. Also, the settings calculated are stored in the lookup table for quick reference when feedback signal of SSSC compensation reached at relay location, it modifies the setting adaptively. In this current study author have not considered any time lag for data transfer between SSSC and relay, as the distance is almost half of line length with optic fiber communication system. In comparison to the published literature available [26-30], the adaptive setting for varying SSSC compensation and fault trajectory showing the fault response with its behaviour have not been shown by the authors. But in this study, authors have considered all the settings dynamically with the varying compensation and fault trajectory during the fault on the line with various case studies which makes this work different than other published works by various researchers.

VII.CONCLUSION

The main contribution of the proposed research work is to measure the relay impedance with SSSC at mid-point of transmission line and represents its relay characteristic impedance for SLG fault. A Modified distance protection setting scheme (adaptive) is proposed with the information of series injected voltage V_{inj} by SSSC at mid-point of line. To change the reach of the relay for different levels of compensation (series) a method of Modified distance protection setting for first zone is proposed. Modified distance protection setting factor is adaptively decreased for lower level of compensation and is increased for larger level of compensation. By comparing the conventional technique with proposed adaptive scheme, it is understood that, there is a noteworthy enlarge in the enclosed area by distance relay and the mal-operation of the distance relay in presence of SSSC has been overcome. The results demonstrate that, with proposed setting scheme the zone of distance relay is increased adaptively and gives an accurate decision of relay trip.

APPENDIX A

Data of Study System (shown in Figure 1).

Study System Elements	**Parametric quantity**
Equivalent Source (1-2)	System Voltage = 500 KV, System Frequency = 50Hz
	$Z_1 = Z_2 = 25.9\angle 80^0 \Omega$
Interfacing Transformer = 3 winding (Y/y/d)	Transformer ratio =500/11/11KV Transformer rating = 200 MVA Transformer Impedance = 0.1 p.u.
SSSC rating	+/- 100 (inductive & capacitive)
Transmission Line (I-II)	Line length = 200 Km
	$Z_1 = 0.51\angle 85.92^0 \Omega / km, Z_2 = 1.385\angle 74.68^0 \Omega / km$

Figure A.1 shows the physical structure of the Bergeron model.

Tower: 3H5 Conductor: chukar Tower Centre 0 [m]			
Cond.	Connection Phasing	X (from tower centre) [m]	Y (at tower) [m]
1	1	40	40
2	2	40]	40
3	3	40	40
Ground_ Wires:1/2” High Strength Steel			
	Connection Phasing	X (from tower centre) [m]	Y (at tower) [m]
1	Eliminated	-2.5	40
2	Eliminated	2.5	40

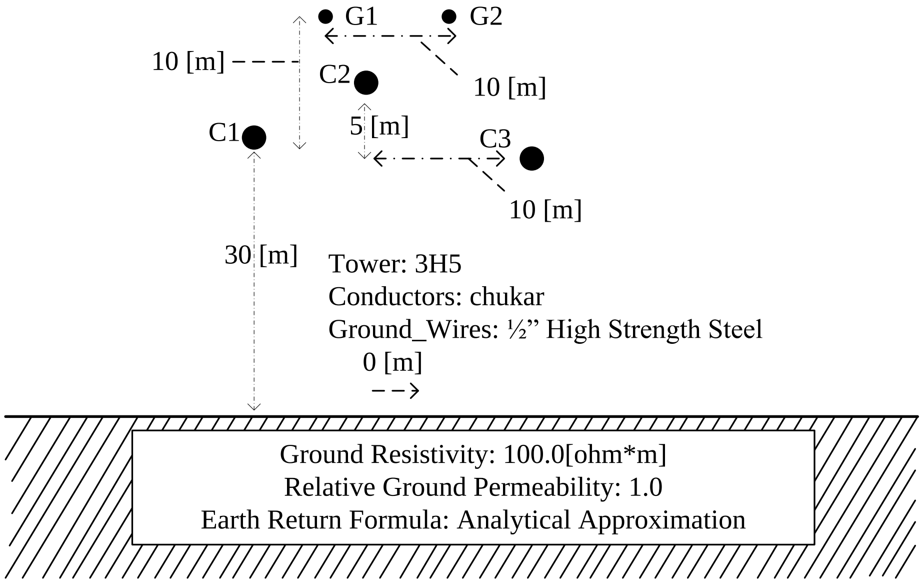


FIGURE A.1. Bergeron model Transmission Line.

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